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D-OPTICAL FIBER AND CLADDING PUMPED OPTICAL FIBER LASERS

Brown University

T. F. Morse

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13. ABSTRACT *(Maximum 200 words)*

This final report presents information in research relating to co-doping of potential cladding pumped optical fibers. The emphasis is on experiments conducted that permitted the comparison of a series of co-doped optical fiber preforms made using an aerosol deposition process developed at Brown University. A set-up was developed that uses ASE (Amplified Spontaneous Emission) as a vehicle by which the relative efficiencies of a series of co-doped Yb-Er optical fibers were examined. These fibers were compared with a fiber from Lucent Technologies. Work on the co-doping of optical fibers to obtain multiple lasing from a Tm-Er system was investigated. This laser permitted pumping at the convenient 980 wavelength to yield lasing at 1550 nm, at 1850 nm, or at both wavelengths. In addition, an attempt was made to extend a new technique that was developed for the tuning of fiber lasers to include the possibility of ultra-fast switching of fiber lasers over a wide wavelength regime. More work is needed in this area, particularly in waveguide design, in order to obtain the required wavelength selectivity.

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D-Optical Fiber and Cladding Pumped Optical Fiber Lasers

Final Report for the
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Introduction

In this final report, we will present information gained over the past year in research relating to co-doping of potential cladding pumped optical fibers. The emphasis will be on experiments that permitted the comparison of a series of co-doped optical fiber preforms made using an aerosol deposition process developed at the Laboratory for Lightwave Technology at Brown University. We first developed a set-up within our laboratory that uses ASE (Amplified Spontaneous Emission) as a vehicle by which we examined the relative efficiencies of a series of co-doped Yb-Er optical fibers. These were compared with a fiber from Lucent Technologies. We also continued work on the co-doping of optical fibers to obtain multiple lasing from a Tm-Er system. This laser permitted pumping at the convenient 980 wavelength to yield lasing at 1550 nm, at 1850 nm, or at both wavelengths. In addition, we attempted to extend a new technique we have developed for the tuning of fiber lasers to include the possibility of ultra-fast switching of fiber lasers over a wide wavelength regime.

Yb-Er co-doped optical fiber lasers

The Yb-Er system has been the main candidate for a high power laser in the Er gain bandwidth from 1527-1572 nm. Yb has a large collision cross section between 910-990 nm, and if pumped in this wavelength regime, energy is resonantly transferred to the Er ions. This then results in lasing at the desired 1550 nm telecommunications bandwidth. Because of Yb's simple electronic energy configuration, there are no problems with ASE. Further, if the pumping occurs at around 915, there is a broad absorption that is relatively insensitive to pumping wavelength shifts. For this reason, even though the 980 line of Yb has a stronger absorption, it is more wavelength dependent. Thus, shifts in the pump wavelength around 915 nm will have little result on the ensuing population inversion. Since the Yb can resonantly pump the Er ions to excite them, there is always the possibility that these excited ions will interact with a ground state Yb ion, and transfer the energy back to the Yb. This clearly results in a loss in lasing photons at 1550 nm. To reduce this effect, since the level that the Yb excites in the Er is above the upper level of the lasing transition, we require that the Er ions excited by the Yb ions decay rapidly to the upper Er lasing level, which is a long lived metastable state. This means that, in

contradiction to the usual situation, we desire a glass with a large phonon energy so that rapid decay to the upper Er lasing level will be enhanced.

A phosphate glass will satisfy this condition. The difficulty, however, is in retaining sufficient phosphorous in the silica fiber, since, during processing, temperatures can reach 2,000 centigrade. We made three Yb-Er co-doped preforms and compared their backward ASE (Amplified Spontaneous Emission) to provide a measure of their lasing efficiencies. In all cases, these were compared with a Yb-Er fiber from Lucent Technologies, and, as phosphorous content of the fibers was increased, the measured backward ASE also increased indicating an increase in lasingefficiency.

The physical and spectral characteristics of these fibers are presented in Tables 1 and 2. In Figure 1 is shown the power measured from the backward ASE. Of particular importance is the peak at which the ASE occurs and the width of the peak. Only the last fiber fabricated in our laboratory approached the efficiency of the Lucent fiber. In Figure 2 and Figure 3 we see measurements of backward ASE of Er pumped at 900 nm and 980 nm. In that which follows, we are interested in the Yb and Er peak ASE intensity when pumped at 900 nm and at 980 nm. The results from an examination of the Yb peak intensities as a function of absorbed pump power shows that pumping at 980 and 900 leads to the same ASE power. This is because there is no contribution to the Yb emission from the excited erbium ions. This is a result of efficient energy transfer and decay to the Er upper lasing level if adequate phosphorous is present in the matrix to create a glass with a higher phonon energy. See Figure 4. It should be noted that there is a difference in the backward ASE of Er at 1550 as a function of the pumping wavelength. The Yb ions are more numerous than the Er ions, and the cross section for absorption is greater for the Yb ions.

In Figures 5, 6, and 7 we show the results for the three fibers that we fabricated with increasing amounts of phosphorous in the core, as tabulated in Table 2. In all of these figures we are measuring the backward ASE at the erbium peak. In Figure 5, the least efficient of our fibers, we see no difference between pumping at 900 nm and 980 nm. In Figure 6, fiber 005, we begin to see some splitting, and in Figure 7, fiber 006, we see a significant amount of splitting. In Figure 8, the ratio of Er/Yb peak intensity is shown, and there is significant improvement when compared with the fiber from Lucent. In addition, it should be noted that our fibers contain 20% less Er than the Lucent fiber, so with an adjustment in erbium content, the agreement would be significantly better.

Er^{3+}-Tm^{3+} Co-doped Silica Fiber Laser

Tm is an interesting candidate for a cladding pumped optical fiber because of its broad gain bandwidth that has applications to laser spectroscopy and ranging for clear air turbulence. It may even prove to be of use in telecommunications applications at the far end of the IR transmission wavelength in silica fiber for shorter distances. At the present time, there are no convenient pigtailed sources with which to pump this ion at 790 nm, so, with a group of researchers from the Laboratory for Lightwave Technology: R.L. Shubochkin, V.A. Kozlov, S.-R. Han and Prof. K. Oh, visiting from the Kwanju Institute of Technology this past summer, we performed some exploratory experiments to see if it would be possible to co-dope a fiber core

with Er and Tm such that if the Er ions were excited, they would transfer energy to the Tm ions, which would then lase. The results of that work are presented in the following.

Co-doping of silica fibers with rare-earth active ions is a promising technique to obtain better fiber laser parameters or new lasing regimes. Tm-doped silica fibers with a broad luminescence band (1.65-2.1 μm) are attractive as active media because of their potential applications in laser medicine and fiber-optic sensors. Er-doped silica fibers are the most common active fibers due to their use as optical amplifiers telecommunications.

This research is concerned with the Er-Tm system in a silica host. We have fabricated Er-Tm co-doped silica fibers to study the energy transfer process from Er to Tm. In particular, we are concerned with fiber laser parameters that are compatible with readily available high power 980-nm pump sources. The spectral characteristics and the performance of Er-Tm fiber lasers are described.

The fiber preforms used in these experiments were fabricated by MCVD (Modified Chemical Vapor Deposition) method with an aerosol delivery technique [1]. The precursors of the glass composition of the core were prepared in water solution of high-purity nitrate salts. Two preforms were fabricated with Er/Tm ions concentration of 6,000 ppm/600 ppm (preform and fiber 1) and 1,200 ppm/6,000 ppm (preform and fiber 2). The fibers were ~125 μm in diameter and each with a cutoff wavelength of ~1.4 μm and numerical apertures of 0.27 (fiber 1) and 0.12 (fiber 2). The fibers were two-mode for 980-nm pump radiation and single-mode for luminescence and laser radiation for both Er and Tm ions.

Er^{3+} and Tm^{3+} ions energy levels important for the Er-Tm system are shown in Fig. 9. For Er ions pumped in the 980 nm spectral range two exited manifolds are of concern for the Er-Tm system: $^4I_{13/2}$ (1.55 μm luminescence band) and $^4I_{9/2}$, (the result of Er ions "pair induced quenching", PIQ). There is also energy transfer to the $^3H_4$ and $^3F_4$ energy levels of Tm^{3+} [2]. Two Tm^{3+} luminescence signals were observed with central wavelengths of 1.4 μm ($^3H_4$-$^3F_4$ transition) and 1.85 μm ($^3F_4$-$^3H_6$ transition).

Using a cw Ti-sapphire laser with output wavelengths in the range of 945-995 nm, ~300 mW were coupled into the fibers for luminescence and laser measurements. Typical luminescence spectra at the output of 2-2.5 m lengths of fibers are shown in Fig. 10a (fiber 1) and Fig. 10b (fiber 2). The pump wavelength was ~978 nm. The $^3F_4$-$^3H_6$ transition luminescence was maximum in comparison with other transitions in both fibers. The presence of 1.4 μm luminescence indicates an energy transfer between Er and Tm ions as well (insets in both Figures 10a and 10b). The upper curve in the inset in Fig. 10a shows the luminescence at the output of the shorter fiber piece. The radiation from the Er main luminescence band is reabsorbed as a consequence of the large Er ion concentration. This is particularly the case in fiber 1. The same re-absorption phenomenon increased the Tm maximum luminescence wavelength in fiber 2 (Fig. 10b). Therefore, having Er concentration higher than that of Tm, appears to enhance the lasing of Tm ions in Er-Tm co-doped fibers.

Laser performance was monitored as a function of the active fiber length, pump wavelength, pump power and cavity mirrors. The most remarkable result is presented in Fig. 11 for a fiber 1 laser with cleaved fiber ends as mirrors. Changing the pump wavelength and fiber length (2-2.5 m) allowed lasing of Er ions (1560 nm, Fig. 11a), Tm ions (1860 nm, Fig. 11b) or

dual-wavelength lasing of both ions (Fig. 3c). The lasing peak intensities were close to each other in the last case. Fig. 4 shows the dependence of the lasing peak intensities on pump wavelength for Er and Tm ions. The length of fiber 1 was 2.4 m, and in this case the Tm peak amplitude was several times larger than that of Er for most pump wavelengths. There was no lasing when the pump wavelength was near 980 nm, close to the Er ion peak absorption. This is probably due to re-absorption in a three level system. However, this broad range of pump wavelengths allows a larger choice of pump sources for Er-Tm fiber lasers.

Bulk laser mirrors butt-coupled with our active fiber increased the lasing power. For an input Tm dichroic mirror (HT for 0.9-1.0 μm and HR for 1.8-2.0 μm wavelength range) and output Tm mirror (95% reflectivity for 1.8-2.0 μm) the output power for lasing Tm ions was in the mW range with two maxima at 955-970 nm and 985-995 nm pump wavelengths. The lasing wavelength changed from 1925 nm at maximum pump power to 1960 nm at the threshold. When the Tm output coupler was replaced with an Er output coupler (98% reflectivity for 1.55 μm spectral range) the Tm ions lasing power increased by 1.5 times but it had also lead to an increase in the laser threshold. The lasing wavelengths were in the 1849-1852 nm spectral range.

In conclusion, we have reported what is to our knowledge the first observation of Er-Tm co-doped silica fiber lasing. With pump source wavelengths between 945 and 995 nm, lasing could be obtained from Er ions (1.55 μm), Tm ions (1.85-1.96 μm) or at both wavelengths at the same time.

Rapidly Tunable Fiber Laser

We now consider a problem that was suggested to us by Paul Payson of Air Force Research Laboratory/SNDR. This involves a possible new method for rapidly switching fiber lasers over a wide bandwidth.

a) Applications

The growth and development of optical communication systems has provided a great interest in the development of rapidly wavelength tunable fiber lasers. Due to its compact size and immunity to electro-magnetic interference fiber lasers are also suitable candidates for sensing an radar applications. Rare earth-doped silica fibers have shown to have a broad emission spectrum, hence, an adequate tuning technique that can provide access to all the wavelengths of interest is of great importance.

Recently, a new technique was proposed to tune fiber lasers in a controllable manner. The arrangement is based on the use of highly overcoupled fused 2x2 fiber couplers (HOCCs), packaged in a low-refractive-index UV curable material with strong temperature dependent refractive index. The HOCCs were used simultaneously as output mirrors and wavelength selective elements. Since the transmission spectrum of the coupler changed with temperature, the mirror's reflection coefficient varied within the tuning range. For specific laser parameters, the optimal coupler transmission determined the lasing wavelength. This tuning technique was demonstrated with both Er^{3+} and Tm^{3+}-doped fibers using a Peltier element to control the

temperature of the HOCC. A 40 nm temperature tuning range and polarization tuning of over 100 nm were obtained with this arrangement [2,3].

For rapidly tunable fiber lasers, the tuning range achieved with the HOCC is very attractive, although the slow response time of the Peltier element will limit considerably the tuning speed. The use of a $LiNbO_3$ waveguide to fabricate an electro-optic tunable HOCC can increase the tuning speed of this arrangement to levels at which the limiting conditions would be imposed only by the losses and the population dynamics of the fiber laser.

In the following we report on the first experiments performed to demonstrate a rapidly tunable fiber laser using an electro-optic tunable loop mirror. The performance of loop mirrors constructed with commercially available $LiNbO_3$ modulators with different internal configurations was investigated.

b) Fiber Loop Mirrors

Fiber loop mirrors have been widely used for all-fiber laser resonators. As shown in Figure 12, the loop is formed by appropriately configuring a single length of fiber before making a directional coupler. The loop reflector is basically a non-resonant interferometer, thus, the description of its performance can be explained by the coherent superposition of fields. For our purposes, it is sufficient to say that the reflection coefficient of the loop mirror is highly dependent on the spectral characteristics and losses of the coupler, a detailed description of its principle of operation can be found in references 4 and 5.

The wavelength dependent coupling coefficient of the 2x2 coupler generates a mirror whose reflection coefficient is wavelength dependent The emission wavelength of a fiber laser using this type of mirror will then be determined by the spectral position of the mirror's peak reflectivity. The reflection coefficient can be changed by changing the refractive index in the vicinity of the coupling region. This will produce a shift in wavelength proportional to the change in refractive index and in this way a tunable all-fiber laser is easily realized. Furthermore, the use of a highly overcoupled coupler (HOCC), with a higher sensitivity to changes in refractive index, increases the tuning range of this arrangement.

If high speed tuning is required, a $LiNbO_3$ HOCC can be employed. Lithium Niobate waveguides have been used successfully to fabricate phase and amplitude electro-optical modulators and although the use of a $LiNbO_3$ device to tune a fiber laser has been proposed previously [6,7], the use of a HOCC-loop mirror configuration can provide a simpler way to fabricate an electro-optical broad-band tunable device for fiber lasers.

c) Experimental results

Several experiments were performed to investigate the performance of commercially available $LiNbO_3$ modulators when configured as loop mirrors. A 2x2 Mach-Zehnder electro-optic modulator, manufactured by Uniphase Telecommunication Products (UTP) was used as the output coupler of a Fabry-Perot fiber laser cavity. A second type of waveguide used for

these experiment was a 2x2 switch, manufactured by Lucent Technologies, which was used in a loop mirror as well as in a ring-laser cavity configuration.

UTP 2x2 Mach-Zehnder Modulator

The 2x2 Mach-Zehnder (MZ) configuration is probably the most commonly used arrangement for electro-optic modulators. This type of device, depicted in Figure 13, uses two 3 dB couplers and the difference in path length in both arms of the interferometer is adjusted by changingthe electric field applied to the terminals connected to the $LiNbO_3$ waveguide. The specified insertion loss for this device is 5 dB, including the coupling losses from the fibers to the waveguide, and the switching voltage is 5 V.

As shown in Figure 13, the output legs of the UTP-MZ modulator were spliced together to form a loop mirror that was used as the output coupler of the Fabry-Perot cavity. The Er3+ - doped fiber was pumped with a 975 nm pigtailed laser diode through a dichroic mirror (highly reflective at 1550 nm and highly transmissive at the pump wavelength), and two polarization controllers were used to adjust the polarization of the light traveling into the modulator (PC1) and to adjust the birefringence inside of the fiber loop (PC2).

The output spectrum of this fiber laser is shown in Figure 14 for different voltages applied to the MZ modulator. It can be seen that for this configuration, changes in the electric field applied to the waveguide do not generate tuning of the laser. It can be noticed however that the laser oscillates in more than one wavelength as the applied voltage increases. This is easily explained by the fact that this type of modulators are intended for communication applications, where the wavelength region of interest comprises a range of about 30 nm centered around 1550 nm. These devices are thus flattened to operate for this broad wavelength region and no wavelength selectivity is obtained when they are used in a loop mirror configuration.

Another limitation imposed by the MZ modulator is that the fixed 0.5 coupling ratio creates a sinusoidal transmission spectrum as a function of wavelength. As suggested in [6], the coupling coefficients of the couplers have to be different than 0.5 in order to obtain a wavelength dependent peak transmission. Hence, the use of a conventional phase or amplitude modulator in a MZ configuration does not provide the desired wavelength selective transmission spectrum needed for a tunable fiber laser cavity.

Lucent Technologies 2x2 Switch.

The internal configuration is shown in Figure 15. Although only one 2x2 switch is shown in the figure the device used for our experiments included 8 switches in a single substrate. Applications for this type of devices include add-drop filters and routers and it is basically constructed by concatenating four Y couplers to form a single 2x2 switch. The switching voltage is 40 V and the specified insertion loss for this switch is 6 dB for TE and TM polarizations. An extra loss of less than 1 dB has to be considered due to the fan-out adapters required to access the fibers coupled to the waveguide.

Two switches were configured as loop mirrors and tested independently. The experimental arrangement was similar to the one used for the UTP switch. For this modulator no lasing was obtained with this arrangement, most likely due to the higher losses of this type of waveguide. The maximum power used to pump this fiber laser was in the order of 100 mW and

some spikes were noticed in the spectrum. This indicates that for higher pump powers lasing should be possible to obtain.

The transmission and reflection of the loop mirror were measured with a fiber laser. The spectra in Figure 16 shows the small reflected signal obtained with this mirror. Changes in voltage for this switch changed only the amount of transmitted and reflected signal.

A second configuration was tried with this modulator. As seen in Figure 17, the switch was used in a ring laser cavity configuration. For this particular arrangement lasing was obtained at the wavelength with minimum losses. Changes in the switching voltage however only increased the number of oscillating wavelengths in the laser cavity. The multi-peak spectrum obtained with this switch indicates that, as with the UTP switch, this modulator does not provide wavelength selectivity and thus the fiber laser cannot be tuned.

d) Future Work

Although it was demonstrated that standard commercially available modulators do not provide the required wavelength selectivity for a loop mirror, other problems related to rapidly tunable fiber lasers can be investigated.

It is well known that relaxation oscillations can limit the speed at which a fiber laser can be tuned. Different methods to overcome this problem have been suggested [8,9] and we are planing to address this problem as well. The experimental arrangement shown in Figure 18, in which two Bragg gratings written at different wavelengths are used as back reflectors for the fiber laser cavity, is intended to measure the speed limitations when the fiber laser changes its resonant wavelength. Experiments are being performed to observe relaxation oscillations and how parameters such as the length of the laser cavity affect the tuning speed. Other causes for speed tuning limitations such as cavity losses and active fiber's parameters (dopant concentration) [10] will also be addressed. Finally, we have also contacted UTP to discuss the possibility of designing and manufacturing a $LiNbO_3$ waveguide specifically intended for a HOCC-loop mirror configuration.

e) Conclusions: Rapidly Tunable Fiber Lasers

The use of a 2x2 HOCC $LiNbO_3$ waveguide in a loop-mirror configuration for rapid tuning of fiber lasers was proposed. The tuning method demonstrated previously in all-fiber configurations provides wide tuning range capabilities making it very attractive for high speed tuning fiber lasers. Two commercially available modulators were tested as loop mirrors and it was concluded that a specific waveguide design is needed to obtain the wavelength selectivity provided by the HOCC. Future work will address the tuning speed limitations of fiber lasers and the possibility of manufacturing a HOCC using a $LiNbO_3$ waveguide.

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Tables and Figures

Fiber	Core composition P_2O_5/ Al_2O_3/ SiO_2, mol%	$\Delta n * 10^{-3}$	$[Er^{3+}]$ ppmwt	$[Yb^{3+}]$ ppmwt
003	0.1 / 1 / 99	~4.6	800	8000
005	2 / 2 / 96	~4.5	≈ 800	18000
006	3 / 2 / 95	~4.5	≈800	18000
121-1 (Lucent)	-	-	1000	10000-20000

Table 1. Physical characteristics of test fibers: fibers 003, 005 and 006 were pulled to have cutoffs at around 1400nm. The cutoff wavelength for the Bell Labs 121-1 fiber is around 900nm.

Fiber	$\tau\ \{^2F_{5/2}\}$ of Yb^{3+} µs	λ_p of Er^{3+} nm	$\Delta\lambda$ of Er^{3+} nm	P_2O_5 mol %
003	-	1531.9	43.1	0.1
005	-	1534.8	35.9	2
006	-	1535.5	33.5	3
ND715 (Southampton)*	-	1535	34	6
121-1 (Lucent)	-	1535.5	20.7	-

* Townsend, J.E. et al.: 'Yb^{3+} sensitised Er^{3+} doped silica optical fibre with ultrahigh transfer efficiency and gain', Electron. Lett., 1991, 27, pp. 1958-1959.

Table 2. Spectral characteristics of test fibers: the data is for backward ASEs measured when pumped with 45 mW at 975 nm for our samples and the Bell Labs fiber.

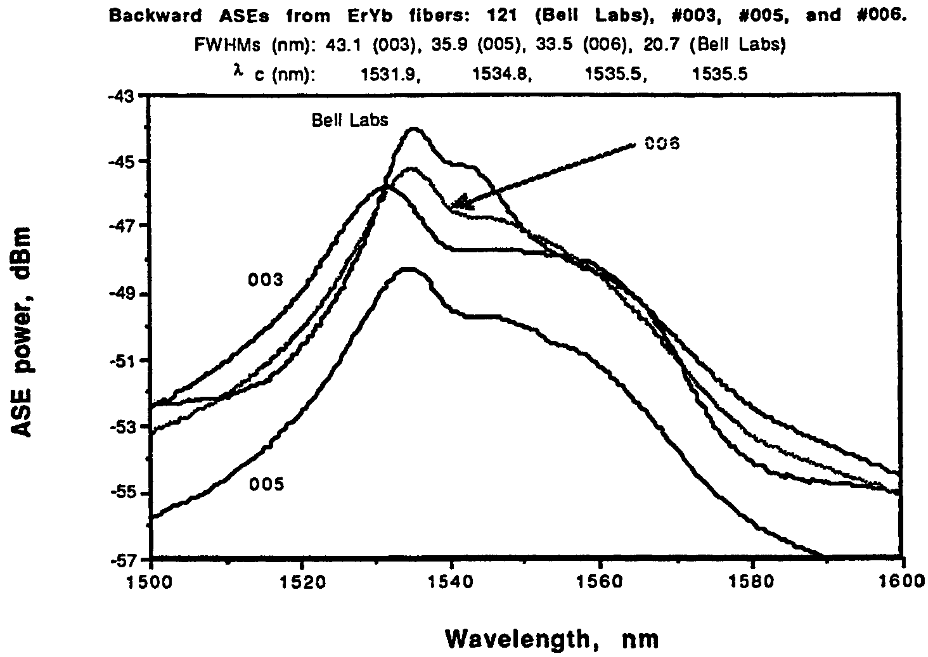


Figure 1. ASE vs. Wavelength: Comparison with Lucent Fiber. Only peak powers have been measured for backward ASEs of Er^{3+} and Yb^{3+}.

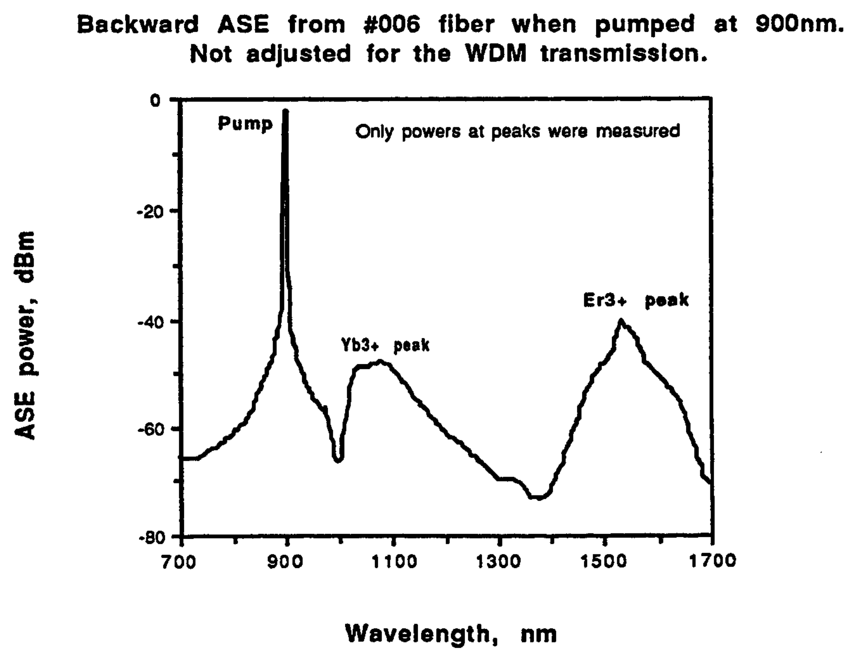


Figure 2. Er^{3+} fiber backward ASE when pumped at 900nm.

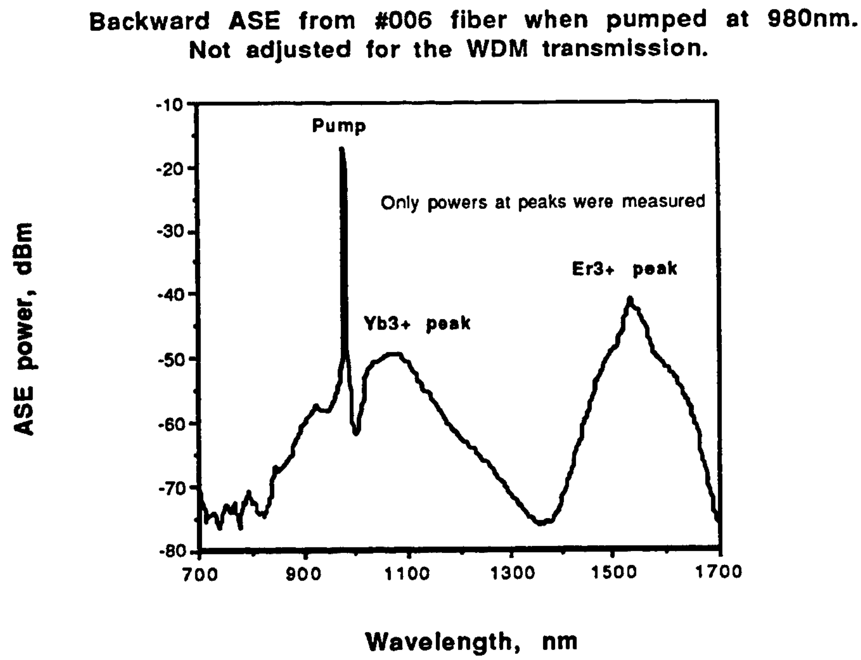


Figure 3. Er^{3+} fiber backward ASE when pumped at 980nm.

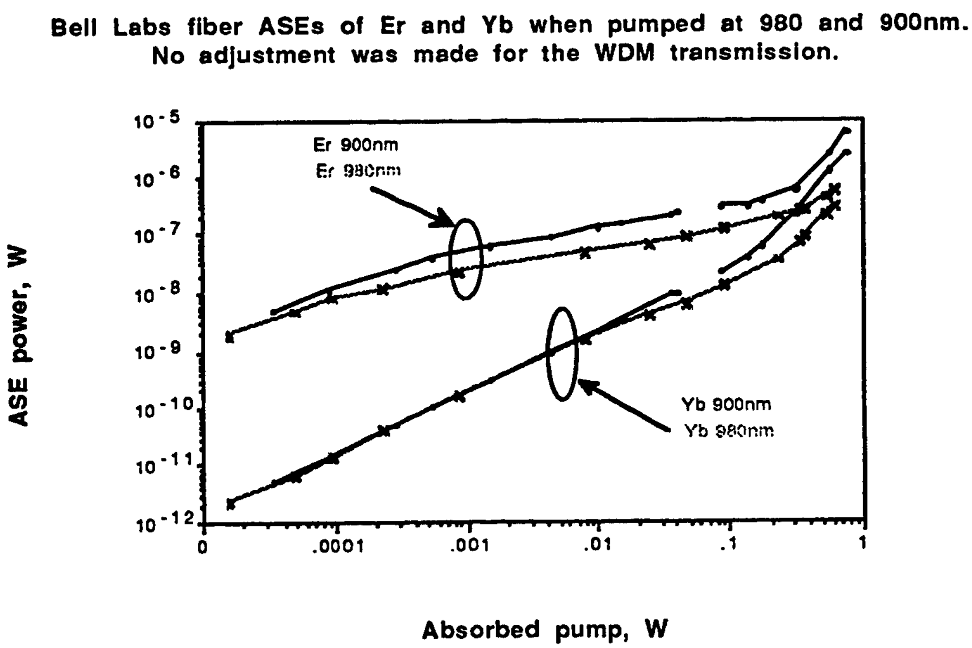


Figure 4. Lucent Yb^{3+} and Er^{3+} fiber backward ASE.

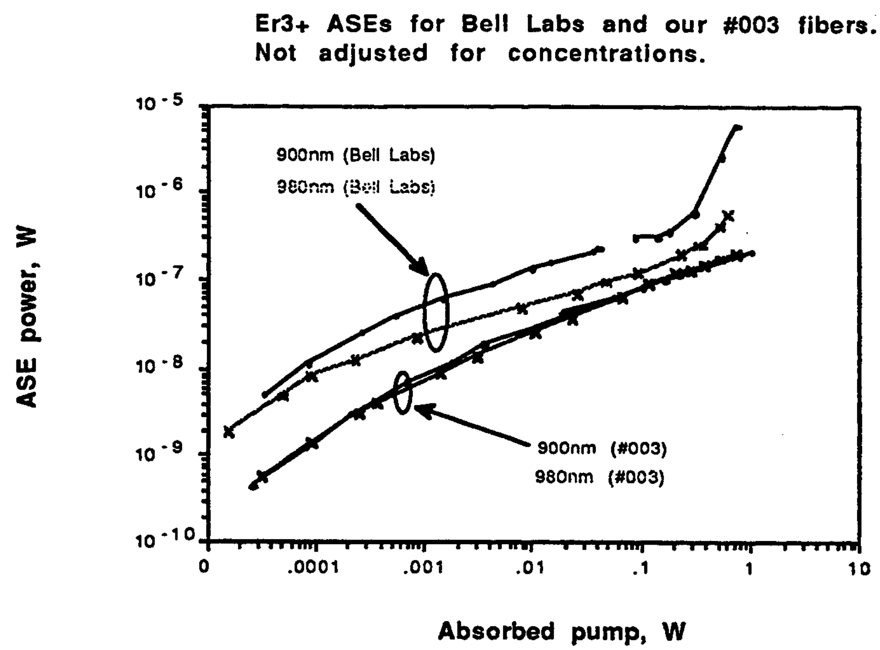


Figure 5. Backward ASE: Fiber #003 compared with Lucent fiber.

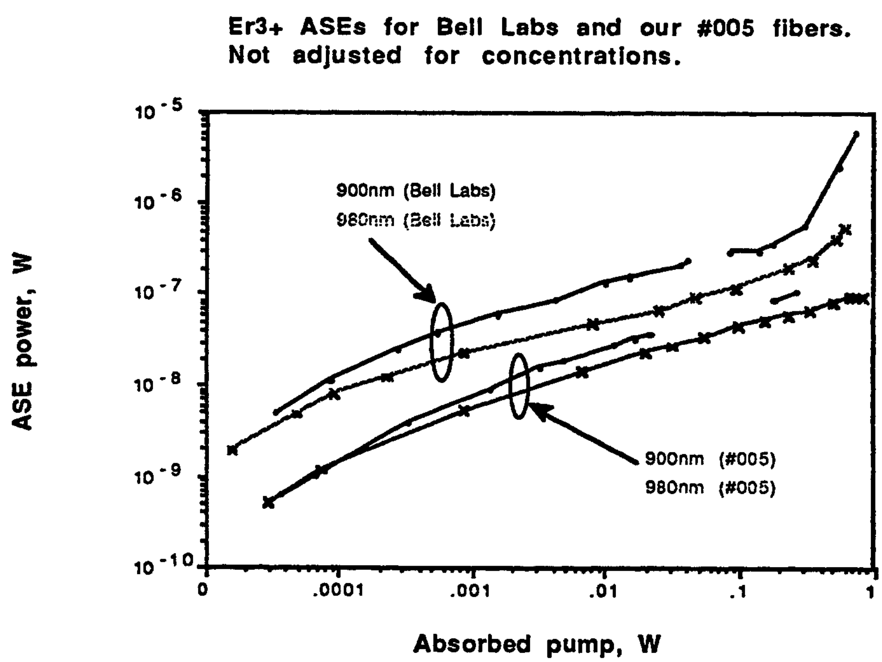


Figure 6. Backward ASE: Fiber #005 compared with Lucent fiber.

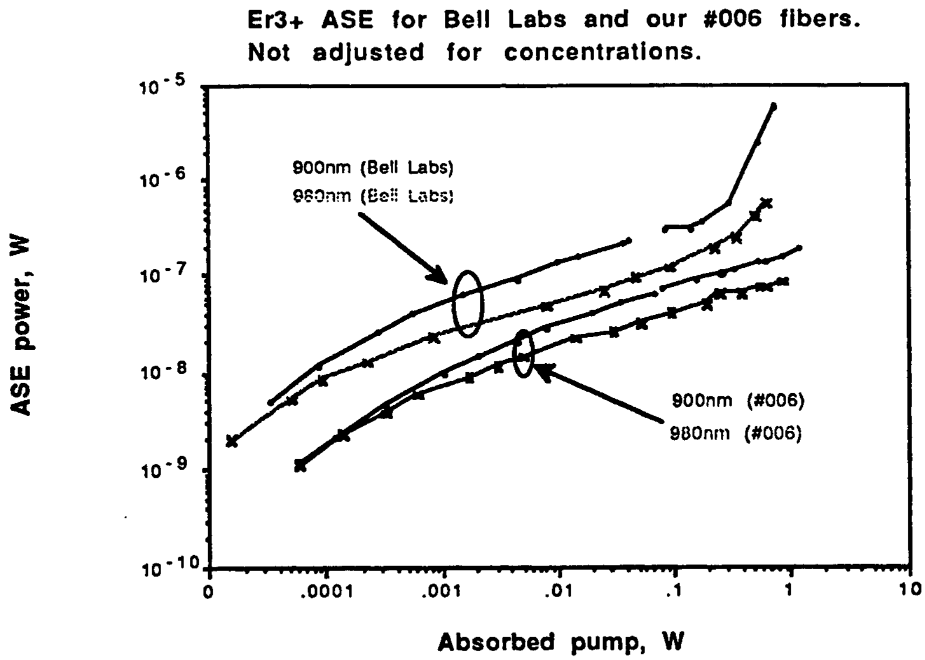


Figure 7. Backward ASE: Fiber #006 compared with Lucent fiber.

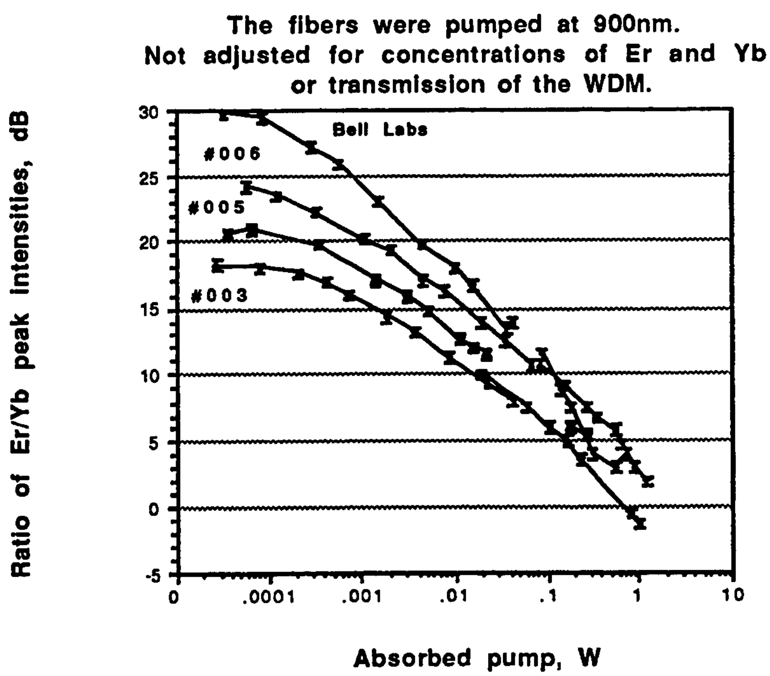


Figure 8. Er^{3+}/Yb^{3+} peak intensities for different pump powers.

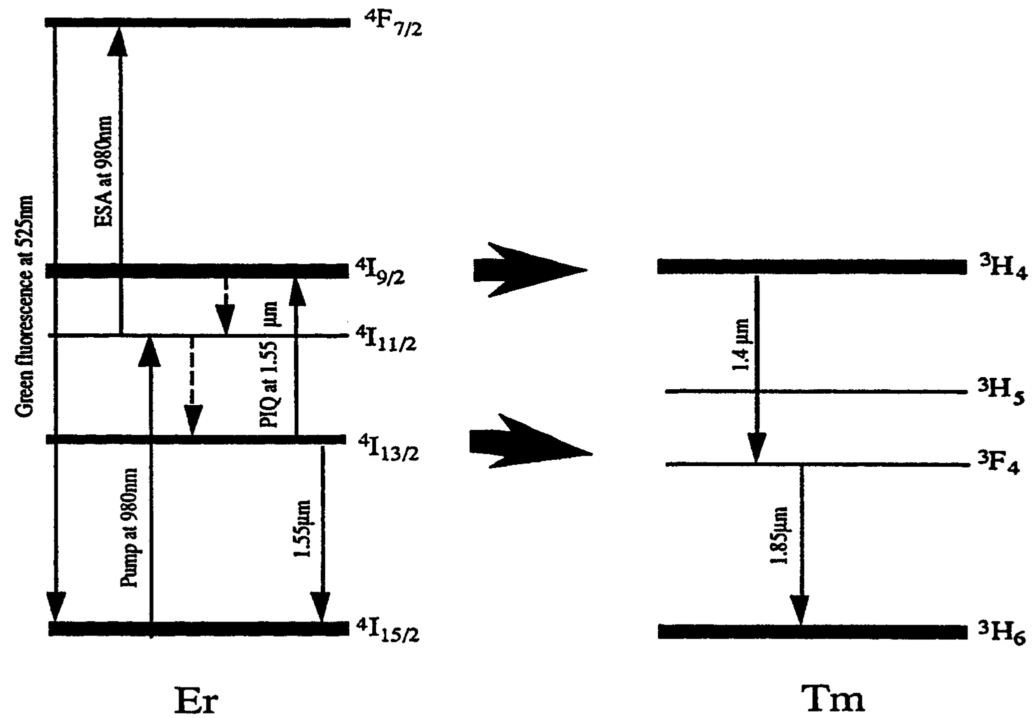


Figure 9. Er^{3+} and Tm^{3+} ions energy diagram.

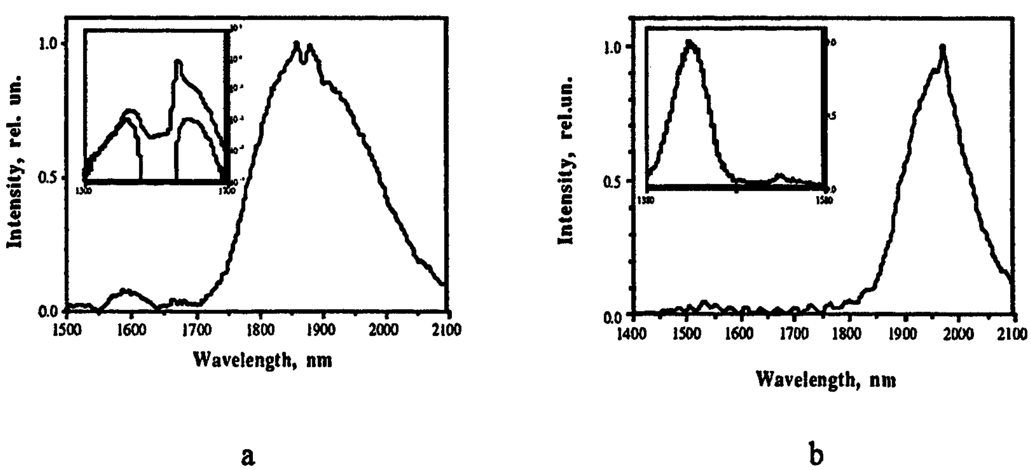
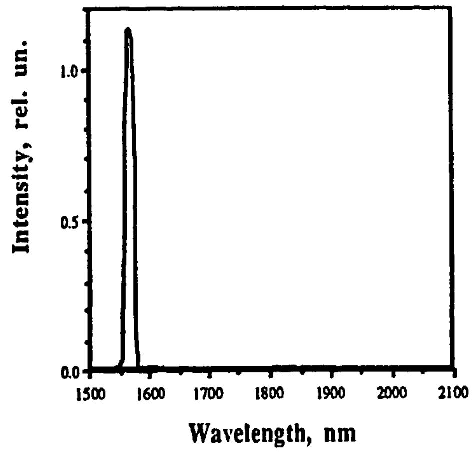
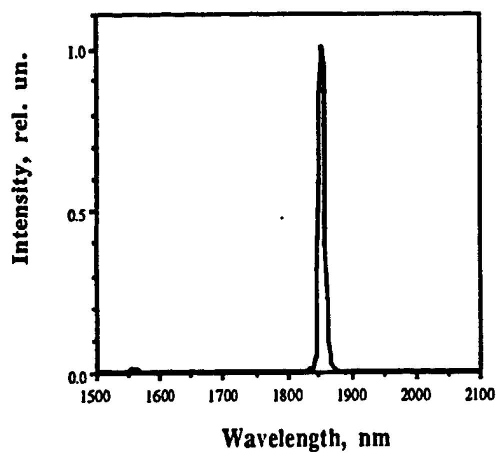


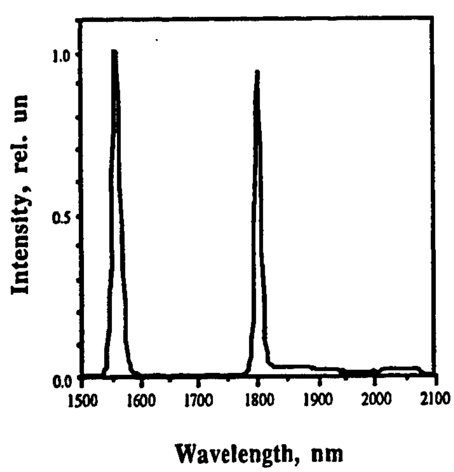
Figure 10. Luminescence spectra of fibers 1 (a) and 2 (b).



(a)



(b)



(c)

Figure 11. Er-Tm fiber laser spectra for Er ions (a), Tm ions (b), and both ions (c) lasing.

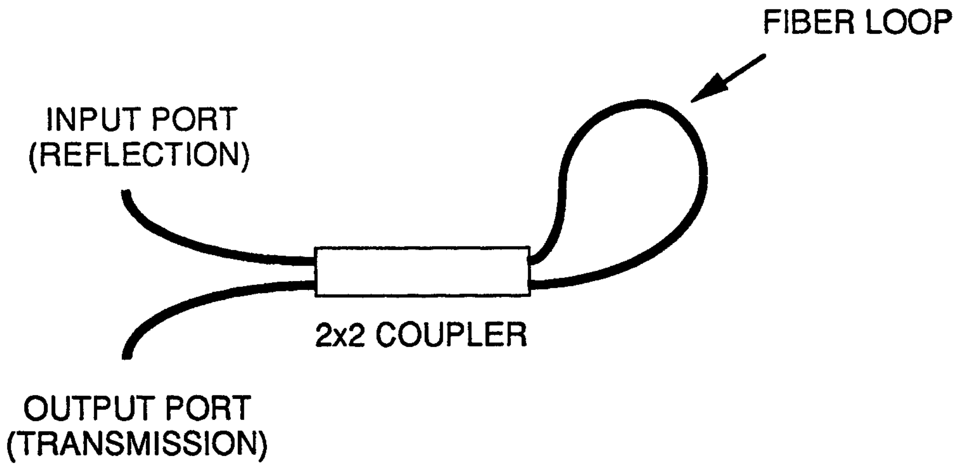


Figure 12. Basic configuration of a loop mirror.

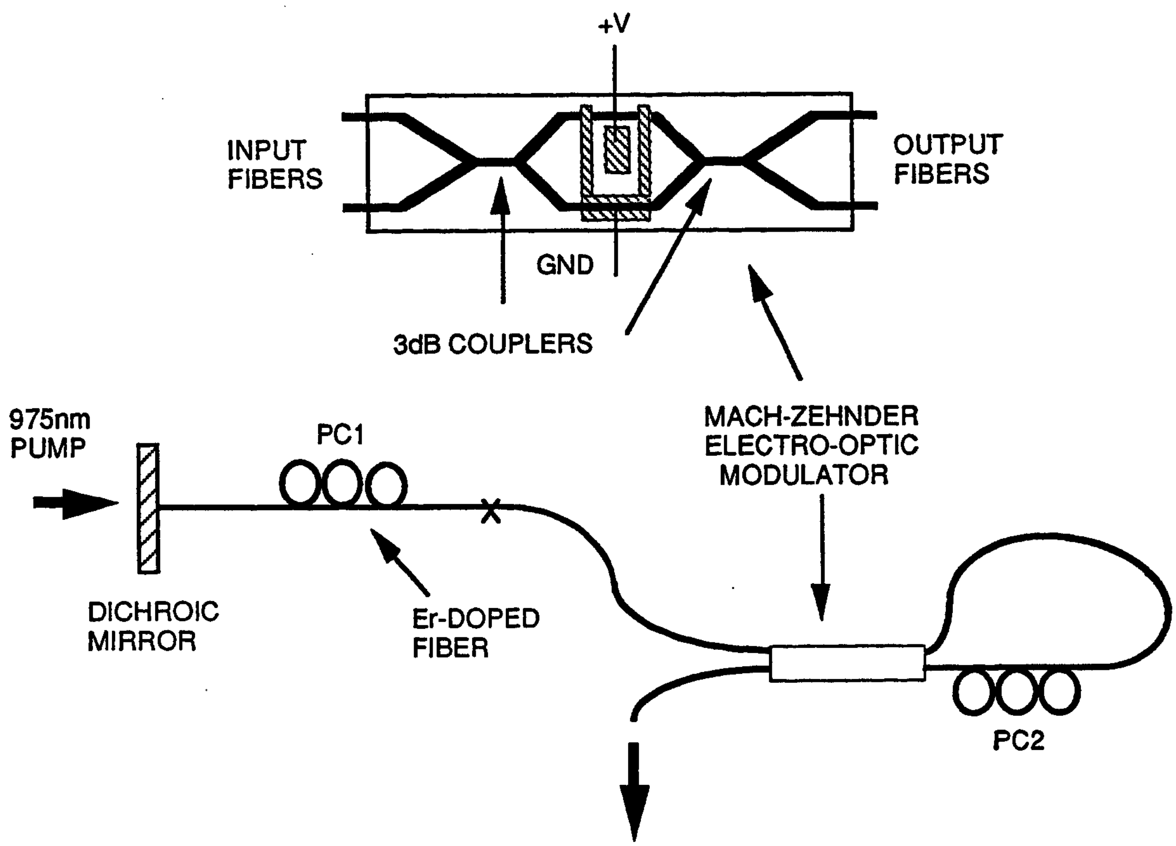


Figure 13. Fabry-Perot laser cavity using a loop mirror as output coupler.

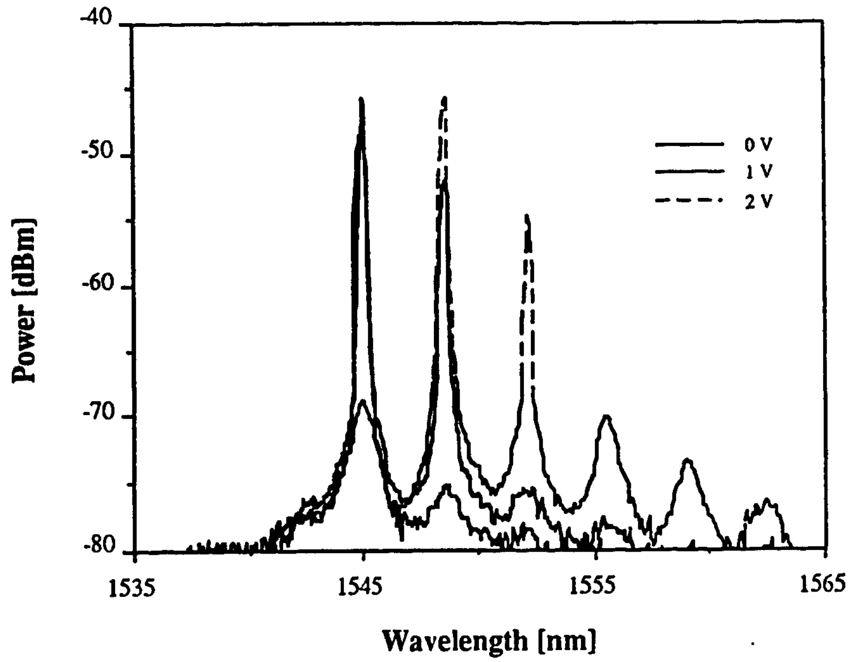


Figure 14. Output spectrum of a fiber laser for different voltages applied to the MZ modulator.

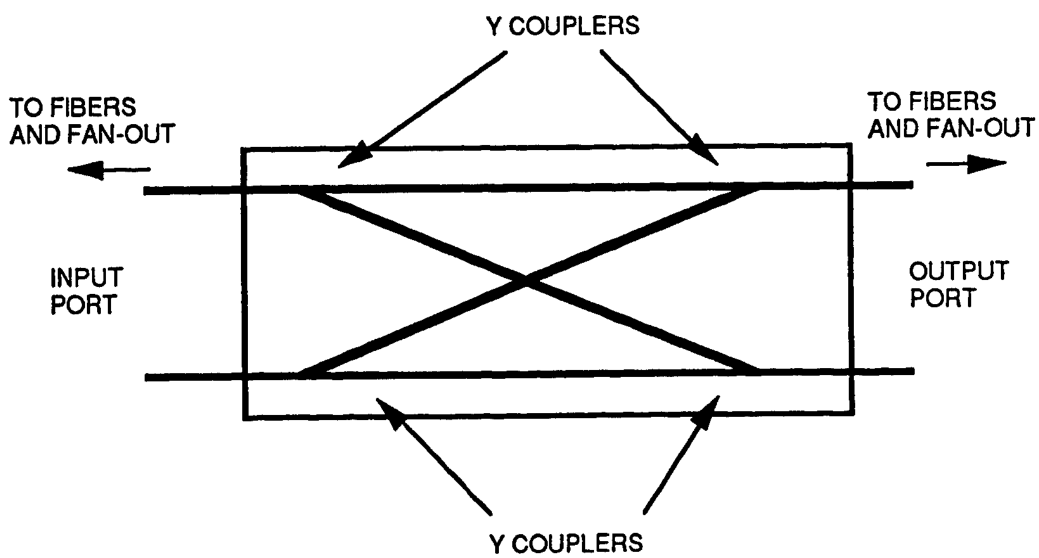


Figure 15. Internal configuration of a 2x2 switch. The device tested has 8 of these switches in a single substrate.

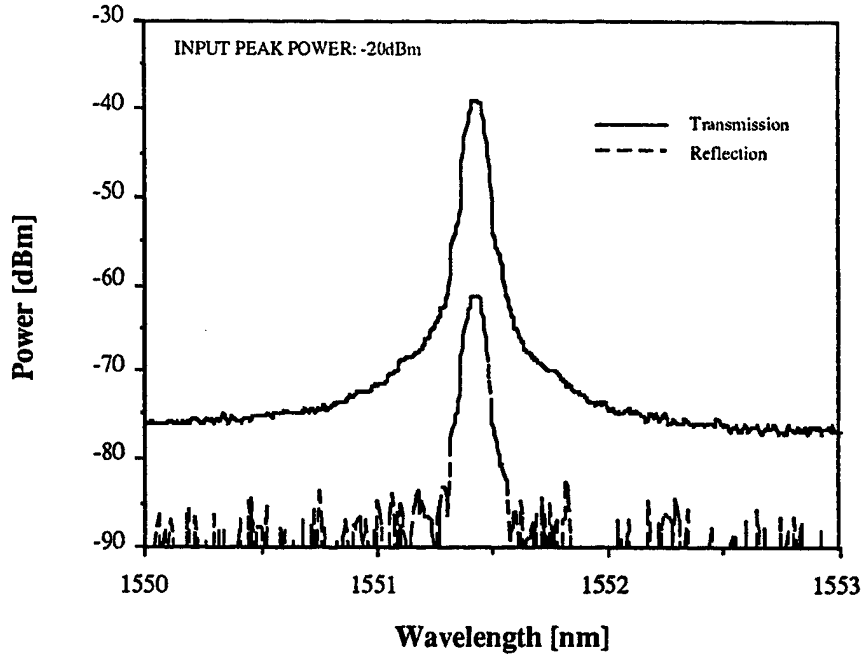


Figure 16. Transmission and reflection of a loop mirror using a 2x2 switch. The reflectivity is estimated to be less than 1%.

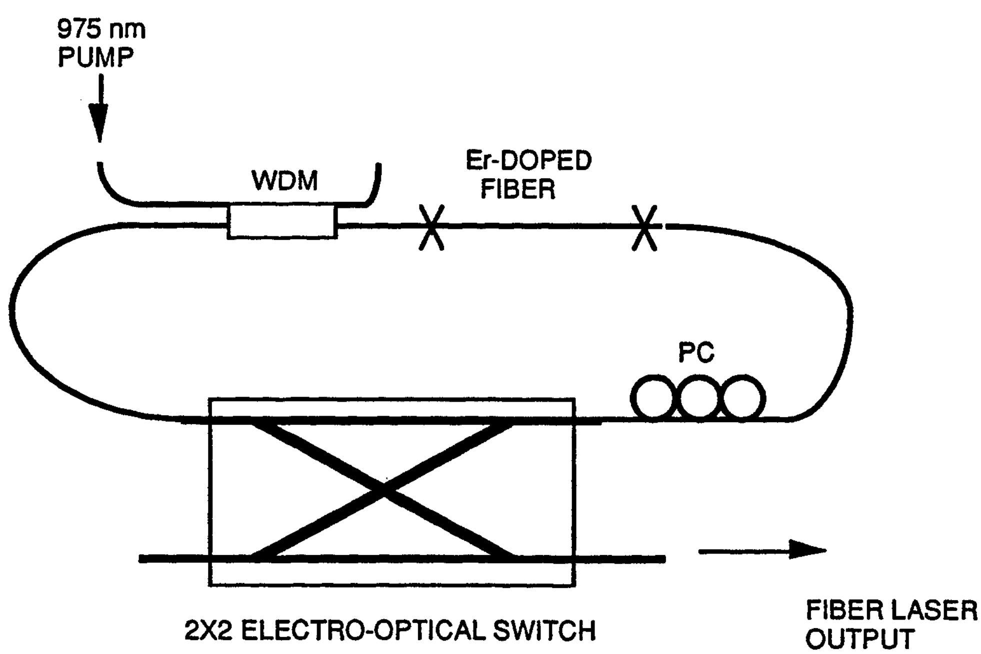


Figure 17. Ring laser cavity configuration.

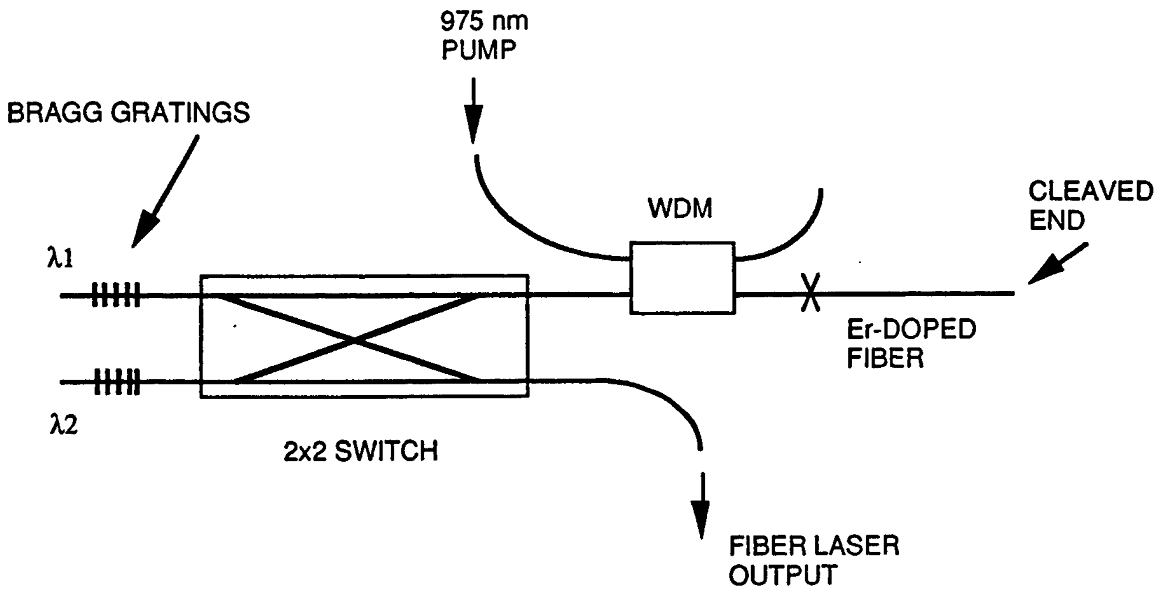


Figure 18. Dual wavelength fiber laser cavity.